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Measurements of Beam Coupling in the Marshall Magnetic Mirror Device

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Plasma propulsion is an advanced propulsion concept that relies on the production of a high density and high temperature plasma. This plasma is ultimately directed out of a confinement system to create thrust. It is predicted that such a system of propulsion is capable of yielding high specific impulse (Isp) given the extreme temperature of the plasma (1). As specific impulse is an important figure of merit for propulsion systems, great interest has been shown in plasma propulsion.

To confine and control a high temperature and high density plasma requires the use of a magnetic field. For propulsion applications, a linear configuration with an open end is preferred to allow for the ultimate ejection of the plasma from the system in order to produce thrust. A magnetic field geometry that meets these criteria is a so-called magnetic mirror. A magnetic mirror is composed of two solenoid coils placed a fixed distance apart. Charged particles in a magnetic mirror are trapped as they move from a weak field region between the coils into a stronger field near each coil (2).

To contribute to the development of plasma propulsion an investigation of the coupling of electrons into a plasma contained in a magnetic mirror has been undertaken. The role of the electron beam is to increase both plasma temperature and density, which are critical factors in plasma propulsion. Electron beams are an attractive source of energy for plasma propulsion, given that high current and high voltage beams are easily produced. The efficient coupling of an electron beam into a plasma propulsion system is, however, dependent on several factors, including: electron beam current, electron beam energy, target plasma temperature and density, magnetic field structure, as well as plasma ion species (e.g. Ar, He, Xe, etc.).

Experimental investigations of the coupling of an electron beam into a magnetically confined plasma have been undertaken at the Marshall Space Flight Center using the Marshall Magnetic Mirror (M3) system. The M3 system is composed of the following: two magnet coils; a cylindrical vacuum vessel; microwave source; and electron beam source. The magnet coils, which form the magnetic mirror, have an inner diameter of 25.4 cm and an outer diameter of 50.8 cm. The coils are composed of 9 coil segments with 33 turns in each segment. Each coil segment is connected in series. To create the target plasma, a 2 kW microwave source (2.45 gHz) is coupled into the vacuum chamber via waveguide. The electron beam source is a hollow cathode device created by the EPL Corporation. The hollow cathode is capable of producing a 50 amp beam with a pulse length of 1 second. It is also capable of continuous operation at 5 amps. The hollow cathode is mounted on one end of the cylindrical vacuum vessel 24 cm outside of a magnet coil. A current sensor is placed in the hollow cathode keeper bias circuit to measure emission current.

Prior to the plasma investigations the magnetic field structure of the M3 system was mapped using a F. W. Bell Series 9950 gaussmeter with a 3-axis Hall Effect probe. The gaussmeter provided the x, y, and z components of the magnetic field at a given location, as well as the magnitude of the vector sum of the components $|B|$. A custom fixture was created to which the probe was mounted. The fixture was moved first radially and then lengthwise through the cylindrical vacuum chamber in approximately 1 cm increments. Plots of the data were made to confirm that no significant errors existed in the mirror field structure. Measurements of $|B|$ were also used to determine the resonant locations for the microwave heating of the target plasma. This was based on: $f = \omega/2\pi = 2.80 \times 10^6$ B, were f is the microwave frequency, and B is the magnetic field strength in Gauss (3). For 2.45 gHz microwaves, the resonant field occurs at 875 Gauss.

To determine the coupling efficiency of the beam plasma system, a set of Langmuir probes was used. One Langmuir probe (LP1) was placed at the center of the mirror coils where the target plasma was created and confined. Another Langmuir probe (LP2) was placed 15 cm outside of the magnetic mirror on the opposite side of the system from the electron beam source. While it is difficult to make absolute measurements of plasma density and temperature with Langmuir probes, accurate measurements of relative changes can be obtained (4). Baseline measurements were made by radially scanning the Langmuir probes across the vacuum vessel cross-section with only the target plasma present. The probe scans were repeated with an electron beam injected into the mirror system. By comparing the plasma properties inside the confinement region and outside of the mirror an assessment was made of how well the electron beam coupled to the target plasma. In the case where target plasma density increased (LP1 location) without a corresponding plasma density increase outside of the mirror (LP2 location), it was concluded that the coupling of the electron beam into the target plasma was positive. On the other hand, where an increase was observed outside of the mirror without a related increase in the confinement region, the coupling of the beam to the target plasma was considered negative (i.e., the electron beam passed through the plasma without significant interaction).

Parameter scans were completed using the Langmuir probe system. Initial scans of electron beam current were conducted using an Argon target plasma. For a fixed microwave power input into the target Argon plasma, the electron beam current was increased from 0 – 6 amps in 1 amp increments. Electron temperature (T_e) and density (n_e) was measured at LP1 and LP2 and compared. To overcome a power supply limit, a pulsed capacitor supply was added to the hollow cathode to allow beam currents of up to 10 amps to be used. Measurements were then compiled for the range of 0 – 10 amps. Next, the effect of gas species on electron beam coupling was studied. For a fixed microwave power (500 W) and beam current (5 A), three different gas species were used in the target plasma. The gases used were Hydrogen, He, and Argon. Again probe scans were conducted for each gas. Finally, to begin to determine the effect of the magnetic field structure on coupling, the coil configuration was changed slightly. With the flexible design of the M3 coil system, each coil segment may be driven independently, subject only to the availability of discrete power supplies. Taking advantage of this flexibility, one coil segment on each of the two mirror coils (defined as a trim coil) was driven independently of the other segments. By changing the ratio of the trim coil current with respect to the rest of the coil pack (i.e., 1/4, 1/2, 3/4, 1) the outside component of the mirror field was changed. For each ratio T_e and n_e were measured at LP1 and LP2.

Experimental results were compiled and compared against basic theoretical predictions. The predictions included plasma particle losses due to the Loss Cone associated with magnetic mirror systems. The loss cone takes into account particles with velocity vectors that are not trapped in the mirror system. Beam-plasma instabilities are also known to exist and represent another loss mechanism for the electron beam energy. First order predictions for losses due to these instabilities are also presented.

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